Climate change adaptation in urban areas

Session B: Extreme rainfall and pluvial flooding in urban areas

Regional Models and geo-Hydrological Impacts (REMHI) Division

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Centro Euro-Mediterraneo sui Cambiamenti Climatici

Quantifying the effect of climate change on flooding
What does this mean?

Understanding which are the components of the water balance affected by climate change

Understanding which are the impacts of those changes on the land and environment (natural or urban areas)

Understanding how to manage those impacts

Extreme rainfall and pluvial flooding in urban areas

Who is in charge of this issues?

Understanding which are the components of the water balance affected by climate change

This is the role of climate modelling!

Everything is cutting-edge research!

Understanding which are the impacts of those changes on the land and environment (natural or urban areas)

This is the role of practitioners, land managers and administrators!

Understanding how to manage those impacts

Extreme rainfall and pluvial flooding in urban areas

There is no consolidated approach/procedure to perform these tasks
This happens because:

Climate modelling is an open topic research

“Perfect” models do not exist

Model results are affected by “uncertainties”

Natural and urban areas respond differently to climate change

Those differences could not be correctly captured by climate modelling

Impact modelling requires additional modelling (e.g. flood modelling)

Usual drainage measures could not be enough

New solutions and approaches should be invoked (e.g. Nature Based Solutions, Low Impact Development, Green Infrastructure)

Dealing with climate change models

1. Identify the variable of interest
2. Select the future horizon of interest
3. Select the RCP scenario of interest
4. Select the climate model ensemble
5. Download data

1. Identify the variable of interest

The **primary effect** of climate change is an increase in temperature.

This immediately affects evapotranspiration. However, evapotranspiration plays a significant role only if large time scales are considered, e.g. for water resources availability evaluations. Floods occur at reduced time scales (e.g. daily, hourly, sub-hourly moving from river flooding to flash floods in urban areas).

The temperature increase of the atmosphere entails an increase in humidity, and, thus, in rainfall. This is a **secondary effect**.

So, we are interested in the **rainfall variable**. But what kind of rainfall? Extreme rainfall!

(Daily) rainfall is an Essential Climate Variable (ECV) provided by climate models. This means that some kind of post-processing is needed to extract the **extreme rainfall regime** of our domain.

2. Select the future horizon of interest

Literature suggests that **time windows of 30 years** are the most reliable since, within those 30 years, climate conditions are homogeneous and, at the same times, they are long enough to draw statistically significant considerations.

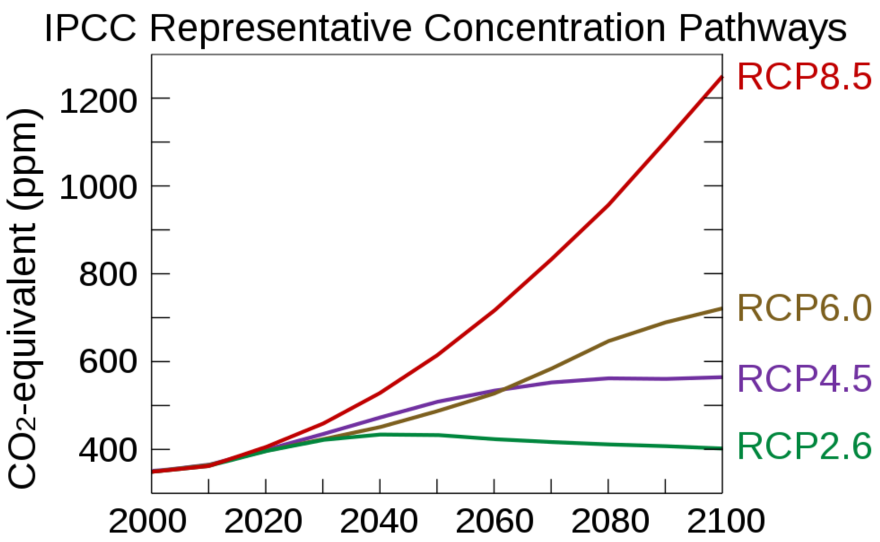
At least two windows are usually considered to represent **short-term and long-term future**. Depending on the purpose of the analysis, possible examples are:

- 2011-2041 (short-term), 2041-2070 (medium-term), 2071-2100 (long-term)
- 2021-2050 (short-term), 2051-2080 (long-term)

3. Select the concentration scenario of interest

IPCC 5th Assessment Report
Representative Concentration Pathways

- **RCP 2.6**
- **RCP 4.5**
- **RCP 8.5**



Each "number" corresponds to the increase in radiative force (expressed in W/m^2) expected by 2100 with respect to pre-industrialized era

3. Select the concentration scenario of interest

IPCC 5th Assessment Report
Representative Concentration Pathways

- **RCP 2.6**: this scenario represents what could happen if **significant** mitigation countermeasures would be applied
- **RCP 4.5**: this scenario represents what could happen if **moderate** mitigation countermeasures would be applied
- **RCP 8.5**: this scenario represents what could happen if **no** mitigation countermeasures would be applied

3. Select the concentration scenario of interest

IPCC 5th Assessment Report
Representative Concentration Pathways

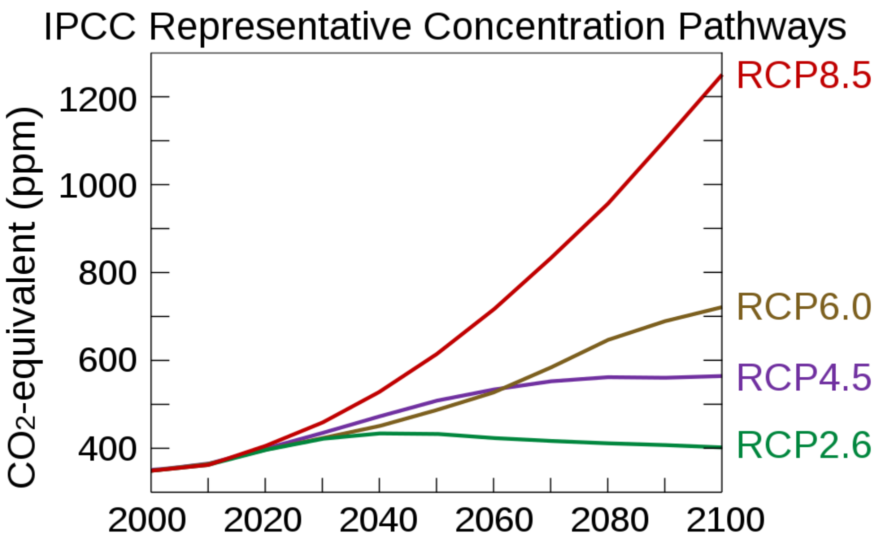
- **RCP 2.6**: this scenario is becoming **less and less probable**
- **RCP 4.5**: this scenario better describes what could happen **in the long term**
- **RCP 8.5**: this scenario better describes what is happening now and what could happen **in the short term**

3. Select the concentration scenario of interest

IPCC 5th Assessment Report
Representative Concentration Pathways

Current practice suggests that the most catastrophic scenario (RCP 8.5) is not reliable because some mitigation practices are bound to be applied.

However, it should be noted that the global warming projected by this scenario has a very good accordance with observations!



4. Select the climate model ensemble

Climate simulations result from the applications of **very complex and computationally heavy climate models**, with a long list of parameters and different possible solution schemes.

This means that, for a given domain (usually trans-national such as Europe), **different climate simulations** exist that are the results of the applications of different Global Models (coarse climate models considered as boundary conditions), Regional Models, parameters' values, numerical solution schemes.

In practical terms, this implies that **an ensemble of climate models** must be considered (namely, downloaded) and dealt with. This is usually done by representing the ensemble by means of the ensemble mean and the standard deviation, considered as a measure for uncertainty.

4. Select the climate model ensemble

For the European domain, climate change evaluations rely on the ensemble of climate models included in the **Euro-CORDEX initiative**, which is the European branch of CORDEX (Coordinated Downscaling Experiment).

The initiative collects climate simulations performed by different institutions, ensuring that **the same domain and horizontal resolution** are kept.

More than 50 simulations are available for Europe. **Reasonable ensembles** collect about 10 simulations.

The ***largest*** the size of the ensemble, the ***better*** uncertainties are accounted for, the ***heavier*** the computations.

https://www.euro-cordex.net/

5. Download data

- Download Essential Climate Variables: raw model outputs such as daily rainfall (gridded dataset) to be elaborated by users, e.g. to extract changes in future rainfall regime

- Download Climate Impact Indicators: post-processed variables that can be directly used in impact models, such as expected changes in Intensity-Duration-Frequency (IDF) curves

- Data are usually downloadable as:

Absolute values (e.g., mm of rainfall)
This usually occurs when downloading climate model results for a reference period, namely, a past time period that we can compare with observations.

Percentage change (% with respect to reference period)
This usually occurs when downloading climate model results for a future time horizon.

5. Download data

The **rawer** the variable, the **heavier** the post-processing you will have to perform to transform climate model results in something that can be directly used in impact models.

To do this, you have to go **deep into the science of climate modelling**, to understand assumptions and limitations. However, dealing with ECV enables estimating tailored quantities (e.g. change in cumulative seasonal precipitation from daily rainfall time series).

Platforms and data repositories (such as Copernicus C3S) exist that **can do this in your place**. However it should be noted that the more extended the domain (e.g. the whole Europe), the rougher the assumptions and the largest the limitations. Finer results could be achieved by including, in the evaluations, local observations for extreme rainfall. However those platforms are valuable to provide preliminary or large-scale evaluations.

Let’s make an example: the SMHI Hypeweb service

https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/

Europe Climate Change

Home > Explore Water > Climate Change Data > Europe Climate Change

CLIMATE IMPACTS

MAPS | GRAPHS AND DOWNLOAD

Indicators and models

Indicator type: Precipitation

Climate impact indicator: -- select --

Impact model ensemble: Ensemble mean

Key Message and Confidence

View Settings

- Absolute mean values (reference period)
- Climate Change Impact period:

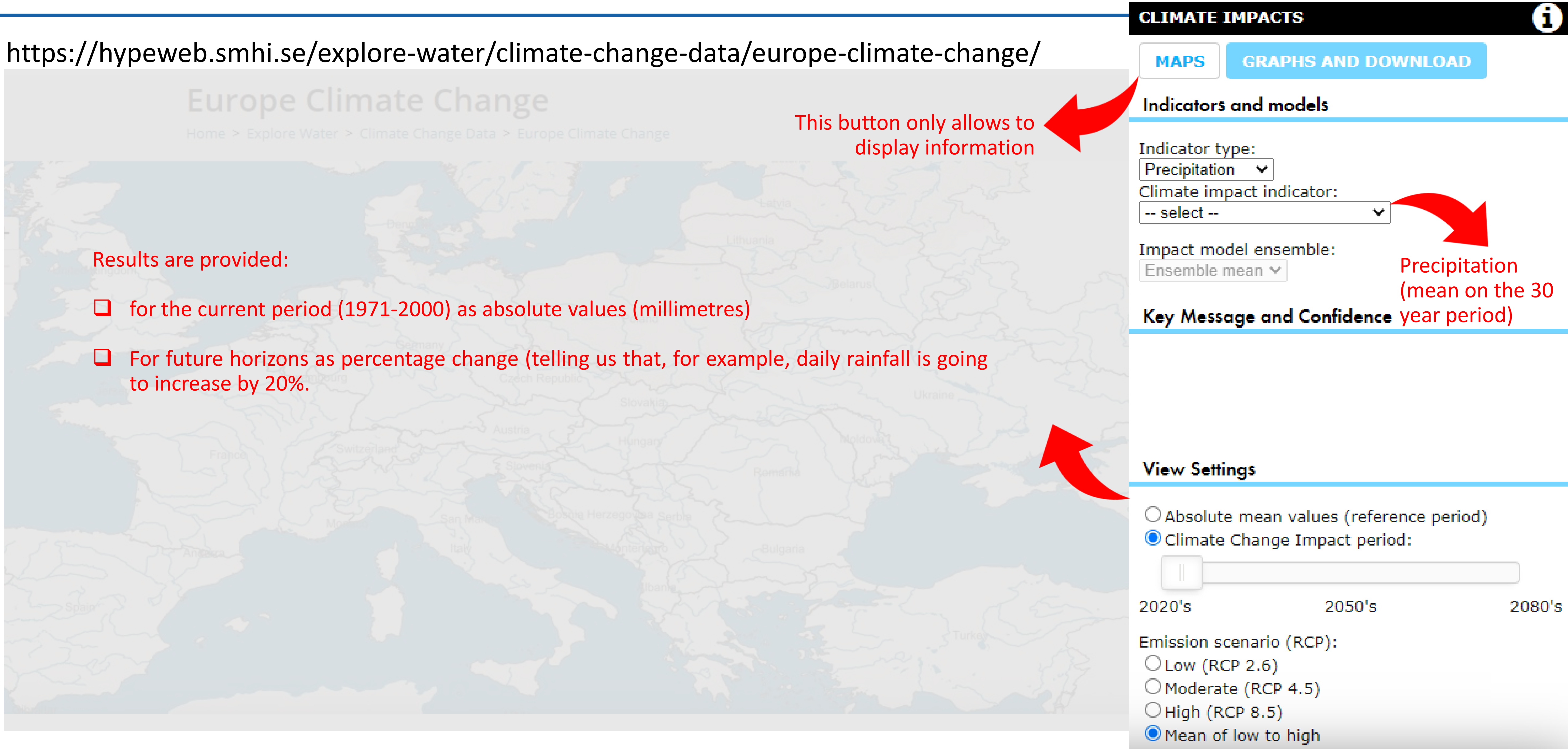
2020's 2050's 2080's

Emission scenario (RCP):

- Low (RCP 2.6)
- Moderate (RCP 4.5)
- High (RCP 8.5)
- Mean of low to high

Let’s make an example: the SMHI Hypeweb service

https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/



This button only allows to display information

Precipitation (mean on the 30 year period)

Results are provided:

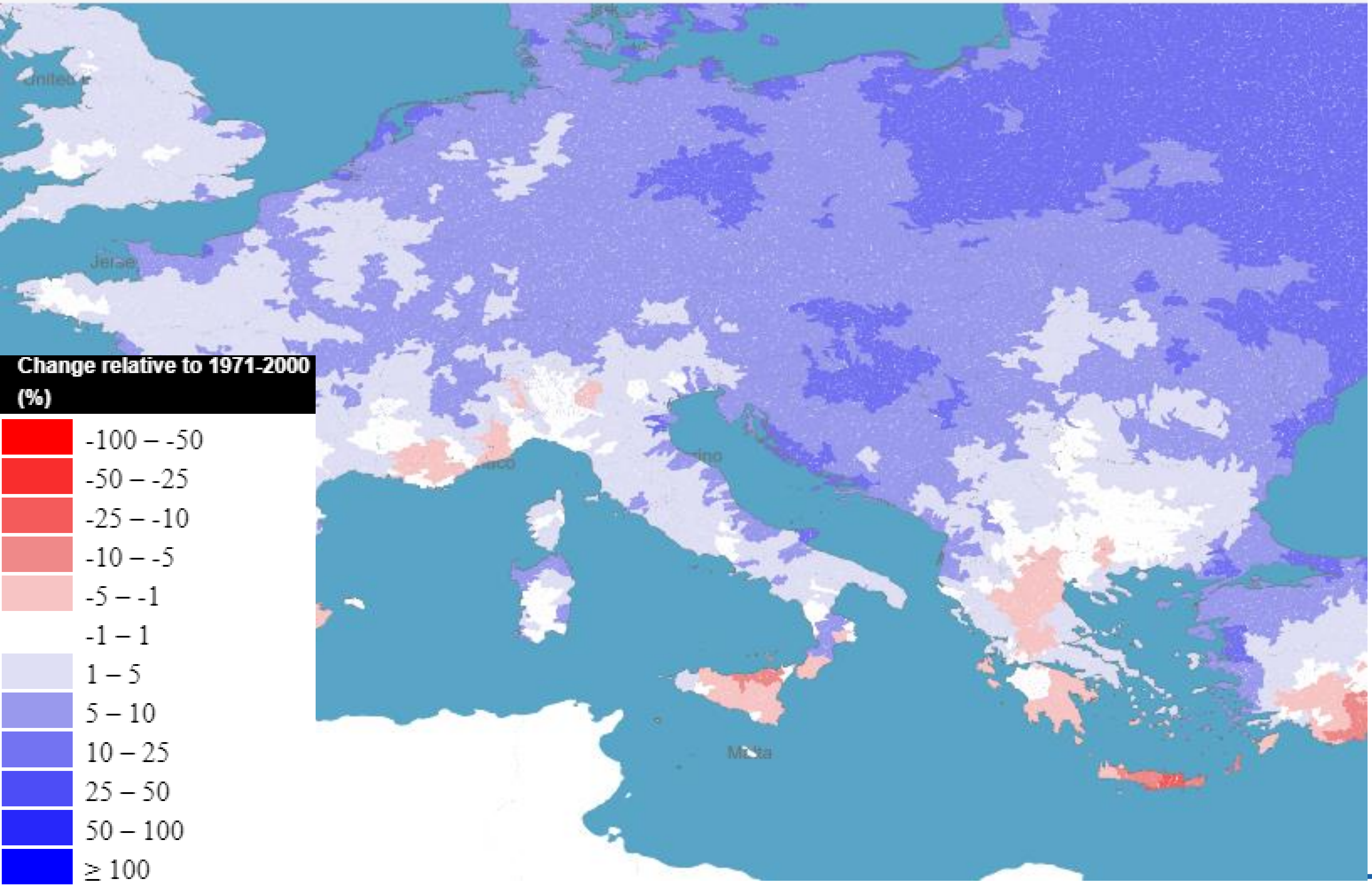
- for the current period (1971-2000) as absolute values (millimetres)
- For future horizons as percentage change (telling us that, for example, daily rainfall is going to increase by 20%.

Let’s make an example: the SMHI Hypeweb service

https://hypeweb.smhi.se/explore-water/climate-change-data/europe-climate-change/

Europe Climate Change

Home > Explore Water > Climate Change Data > Europe Climate Change



CLIMATE IMPACTS

MAPS | GRAPHS AND DOWNLOAD

Indicators and models

Indicator type:
Precipitation

Climate impact indicator:
Precipitation (mean)

Impact model ensemble:
Ensemble mean

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Europe Climate Change

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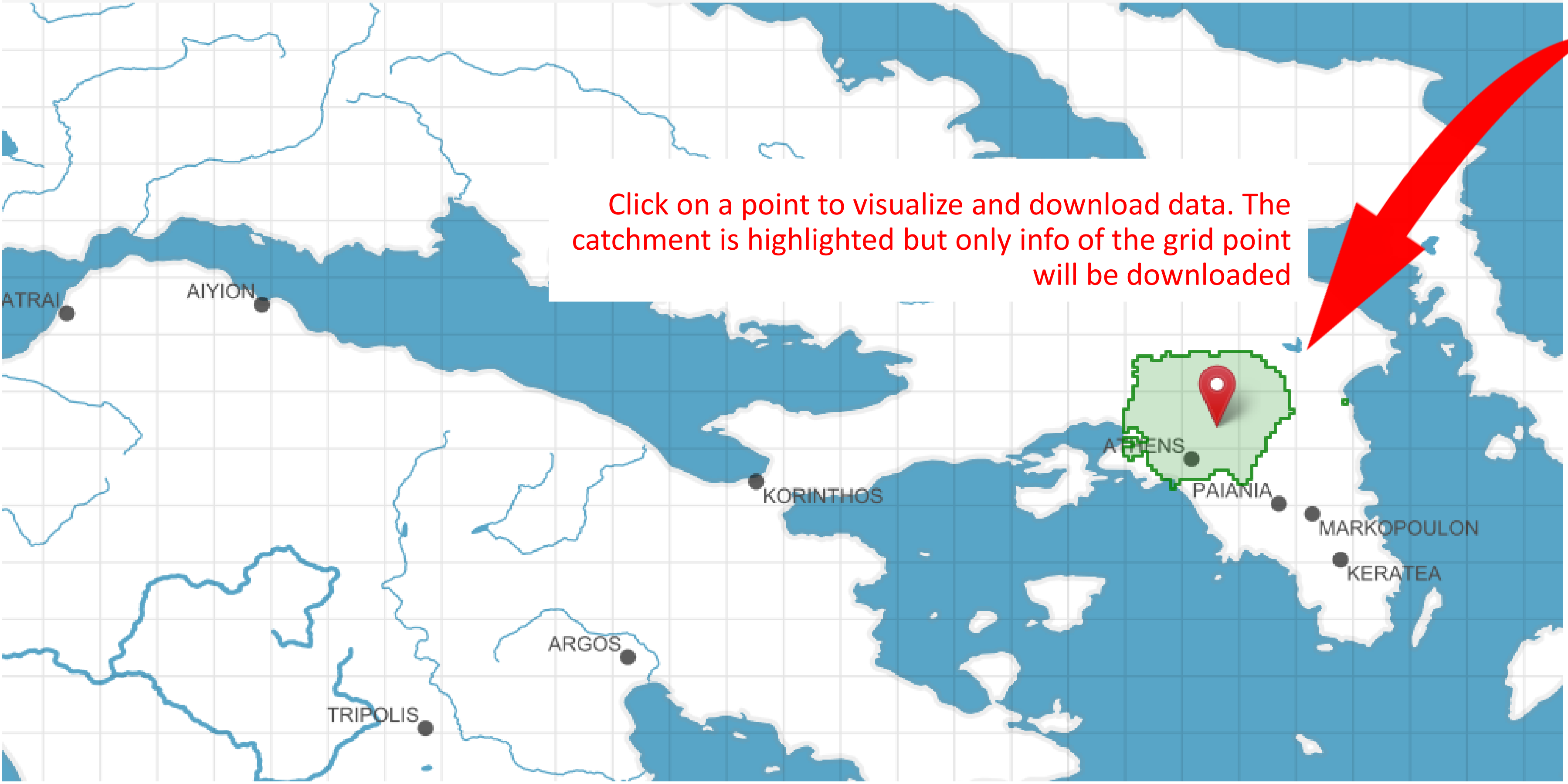

Select coordinate

Click in map to select coordinate or fill in coordinate below

Selected coordinate: 38.04, 23.76
Catchment subid: (N/A)

Lat: Lon: Select

Indicators and models

Indicator type:
Precipitation

Indicator:
Precipitation Intensity duration

View Settings

Emission scenario (RCP):
- Low (RCP 2.6)
- Moderate (RCP 4.5)
- High (RCP 8.5)
- Mean of low to high

- Absolute values (reference period)
- Climate Change Impact period:

2020's 2050's 2080's

Month: N/A

Download data

Download CII

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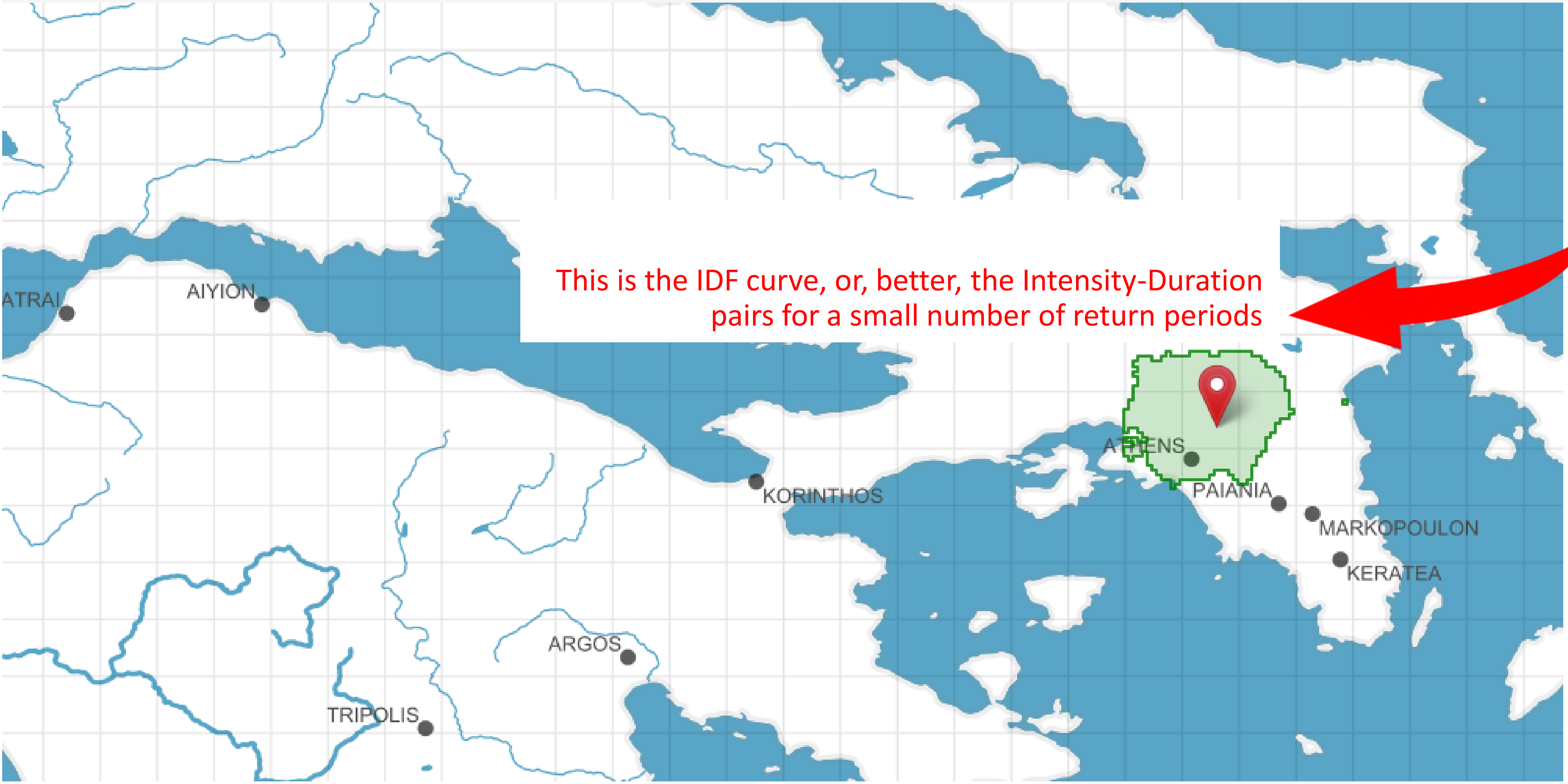
Europe Climate Change

Home > Explore Water > Climate Change Data > Europe Climate Change



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Selected coordinate: 38.04, 23.76
Catchment subid: (N/A)

Lat: [ ] Lon: [ ] Select

Indicators and models

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Indicator: Precipitation Intensity duration

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- Absolute values (reference period)
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2020's 2050's 2080's

Month: N/A

Download data

Download CII

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Europe Climate Change

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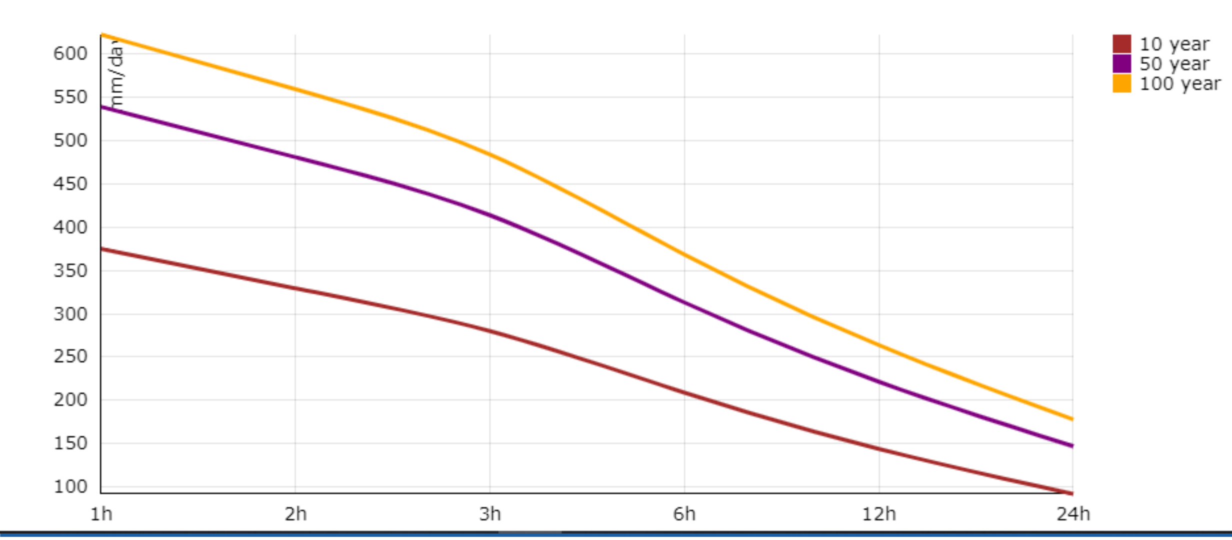
Selecting “absolute values” the graph appears

Precipitation Intensity duration



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2020's 2050's 2080's

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Download data

Download CII

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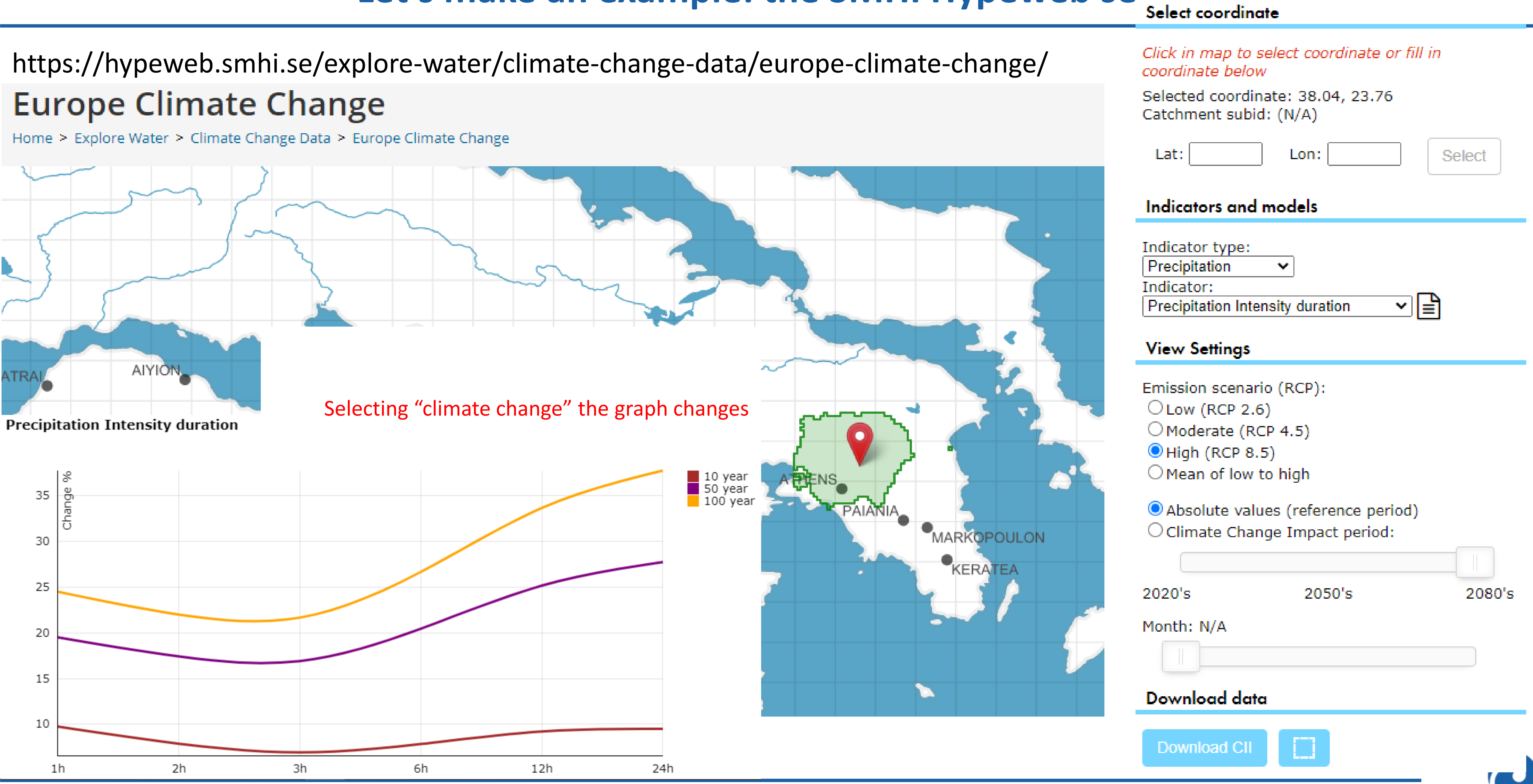

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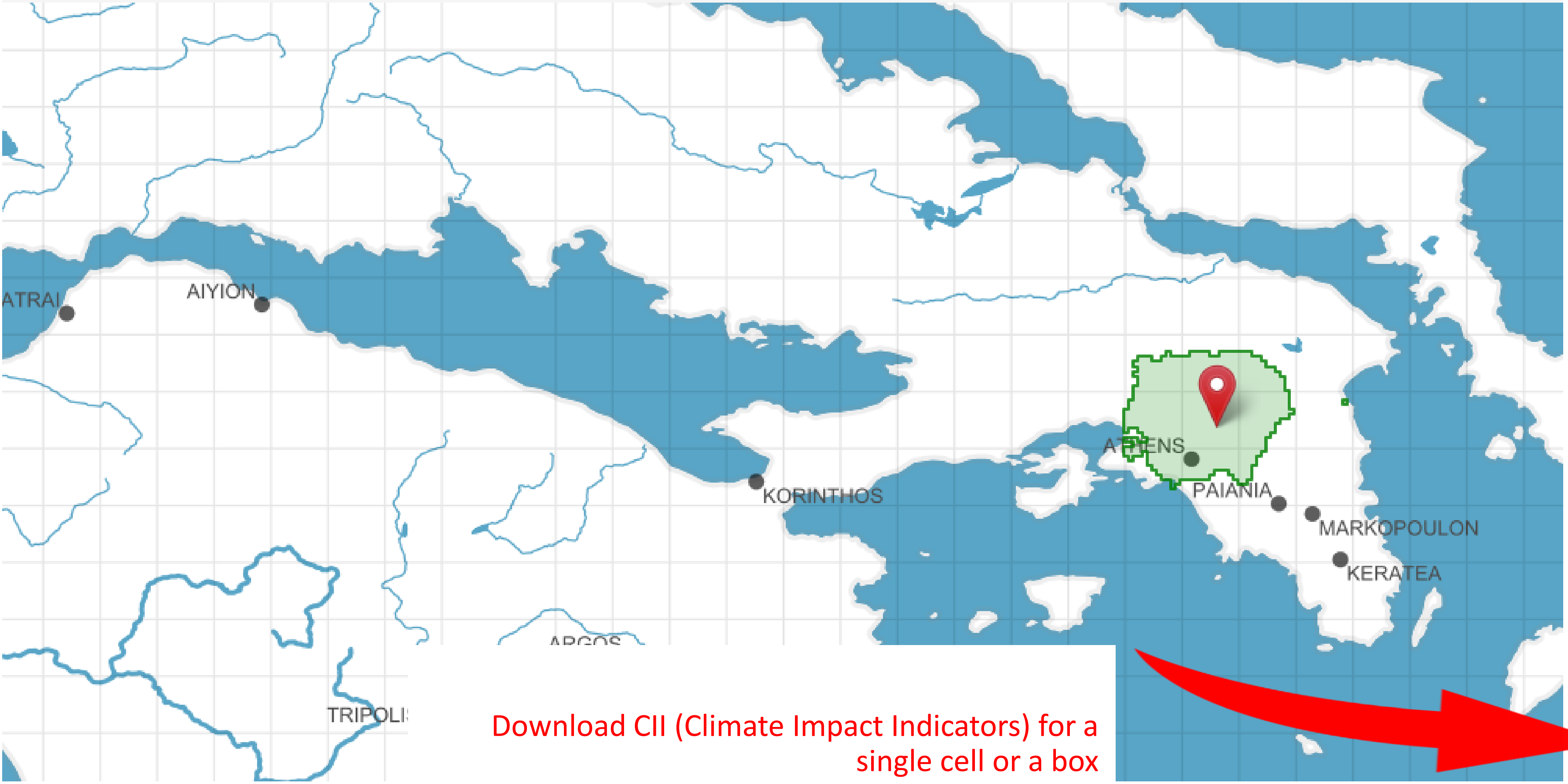

Download CII (Climate Impact Indicators) for a single cell or a box

Select coordinate

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2020's 2050's 2080's

Month: N/A

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Download Climate Change Data

“Summary” sheet

Average change = the value we are looking for (ensemble mean, average value over 30 years, average value across al return periods)

Standard deviation = gives information about the dispersion caused by the use of multiple projections (also **max/min**)

n = number of climate models of the ensemble (could be different for different RCPs)

Agreement = % of climate models giving the same sign of the average change

Average change expected in a future time window centered on the 20’s (2011-2041)

Change 2020							
relative to baseline		1h [%]	2h [%]	3h [%]	6h [%]	12h [%]	24h [%]
full	**average change**	7	8	10	16	19	19
ensemble	standard deviation of change	14	12	13	12	14	18
n=27	maximum change	33	28	35	38	48	65
	minimum change	-11	-9	-8	-4	-2	-14
	agreement on sign of change	48%	67%	67%	89%	89%	89%
RCP45	**average change**	2	3	4	9	11	10
	standard deviation of change	14	10	9	9	9	13
n=15	maximum change	33	22	21	22	29	34
	minimum change	-11	-9	-8	-4	-2	-14
	agreement on sign of change	20%	60%	60%	80%	80%	80%
RCP85	**average change**	13	15	18	24	28	31
	standard deviation of change	10	12	13	11	13	16
n=12	maximum change	28	28	35	38	48	65
	minimum change	-1	-7	-5	5	7	13
	agreement on sign of change	83%	75%	75%	100%	100%	100%

The higher the agreement and the smaller the standard deviation, the more robust the projection!

Download Climate Change Data

"Summary" sheet

Return period = only T=10 yr, T=50 yr and T=100 yr are provided (other could be interpolated)

Duration = different sub-daily durations are considered (>1 hr)

Results given by the climate models for the reference period (1971-2100)

Reference period							
reflects different baseline climate models in ensemble							
		1h [mm/day]	2h [mm/day]	3h [mm/day]	6h [mm/day]	12h [mm/day]	24h [mm/day]
returnPeriod50	average change	474.950	402.429	343.722	245.005	166.069	106.272
	standard deviation of change	65.995	53.094	42.626	30.667	22.355	7.948
n=5	maximum change	543.622	479.802	411.554	294.508	205.203	118.110
	minimum change	377.927	327.903	288.334	202.745	136.851	94.696
returnPeriod100	average change	549.513	468.116	401.985	289.420	198.633	128.681
	standard deviation of change	81.787	66.170	53.508	38.301	28.676	8.992
n=5	maximum change	634.955	568.663	490.737	354.279	251.259	143.574
	minimum change	434.904	381.555	339.487	241.443	165.644	118.481
returnPeriod10	average change	328.403	274.824	231.958	161.341	106.124	65.932
	standard deviation of change	39.167	31.572	25.382	18.490	12.868	6.336
n=5	maximum change	368.022	314.582	266.320	186.285	124.443	72.592
	minimum change	263.429	222.924	190.915	130.604	84.756	54.349

Baseline values can be quite different from the observations. A good strategy is that of retaining only the anomaly (i.e. the change)

Download Climate Change Data

"returnPeriod10-2020" sheet (and similar)

If you want to compute a possibly different change for each return period you can manipulate data reported in the other sheets

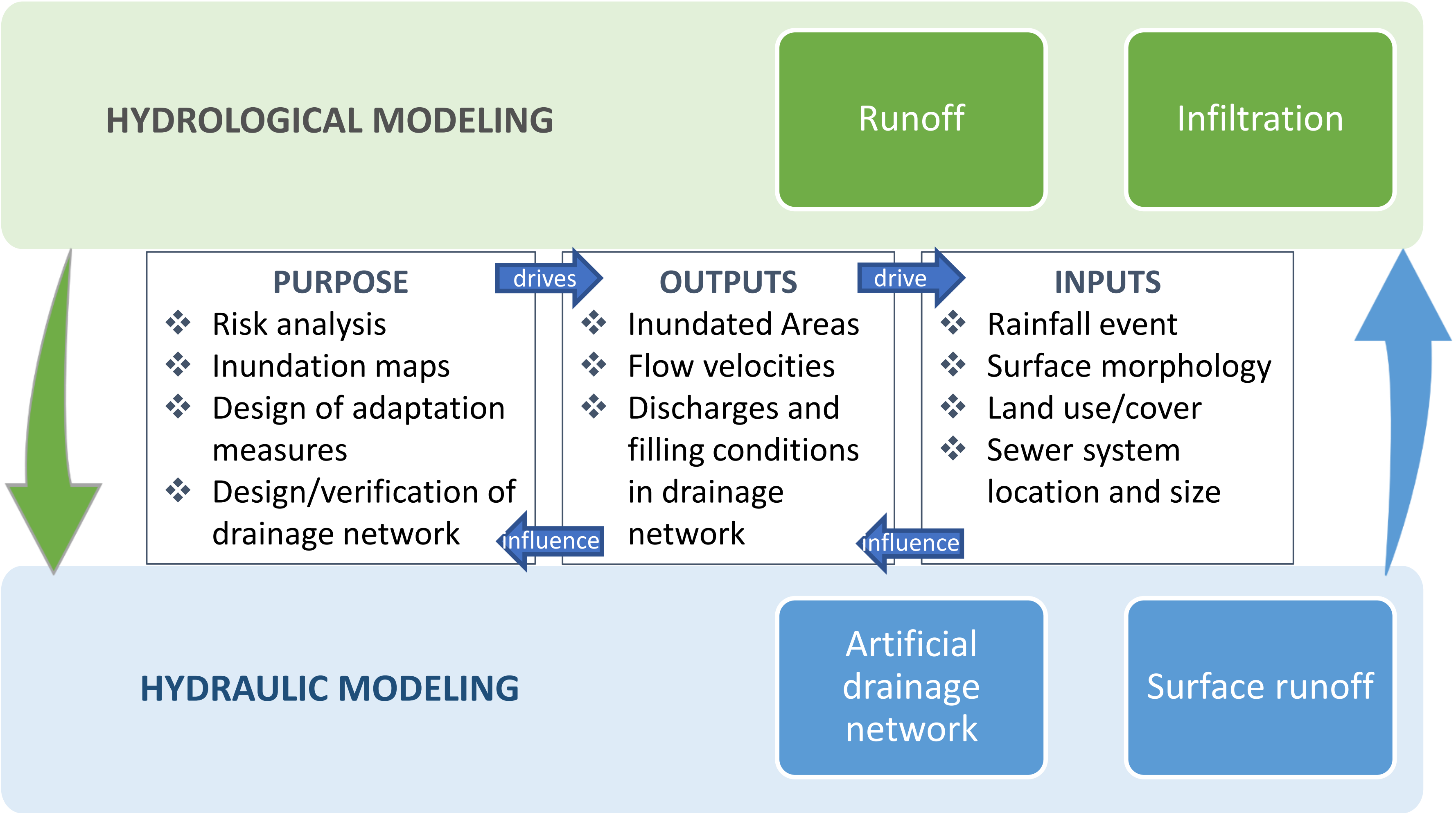
	2011-2040 ('20s) Member (e.g RCP 4.5)	1h [%]	2h [%]	3h [%]	6h [%]	12h [%]	24h [%]
RP 10	CNRM-CERFACS-CNRM-CM5-rcp45	25	20	19	17	11	-3
	ICHEC-EC-EARTH-rcp45	-3	1	3	6	3	1
	IPSL-IPSL-CM5A-MR-rcp45	-7	-6	-4	2	9	12
	MOHC-HadGEM2-ES-rcp45	-3	3	5	15	18	21
	MPI-M-MPI-ESM-LR-rcp45	-1	-1	-1	-1	-1	4
RP 50	CNRM-CERFACS-CNRM-CM5-rcp45	31	22	20	18	11	-10
	ICHEC-EC-EARTH-rcp45	-6	1	4	9	8	5
	IPSL-IPSL-CM5A-MR-rcp45	-10	-8	-7	3	16	20
	MOHC-HadGEM2-ES-rcp45	-6	2	5	20	25	30
	MPI-M-MPI-ESM-LR-rcp45	-2	-2	-3	-3	-2	7
RP 100	CNRM-CERFACS-CNRM-CM5-rcp45	33	22	21	18	11	-14
	ICHEC-EC-EARTH-rcp45	-7	1	4	11	10	6
	IPSL-IPSL-CM5A-MR-rcp45	-11	-9	-8	3	20	23
	MOHC-HadGEM2-ES-rcp45	-7	2	5	22	29	34
	MPI-M-MPI-ESM-LR-rcp45	-3	-3	-4	-4	-2	8
	Average RP 10	**2**	**3**	**4**	**8**	**8**	**7**
	Average RP 50	**1**	**3**	**4**	**9**	**12**	**10**
	Average RP 100	**1**	**3**	**4**	**10**	**14**	**11**
	Average	**2**	**3**	**4**	**9**	**11**	**10**

You can check consistency and understand which is the dispersion of the models

PLAYTIME!

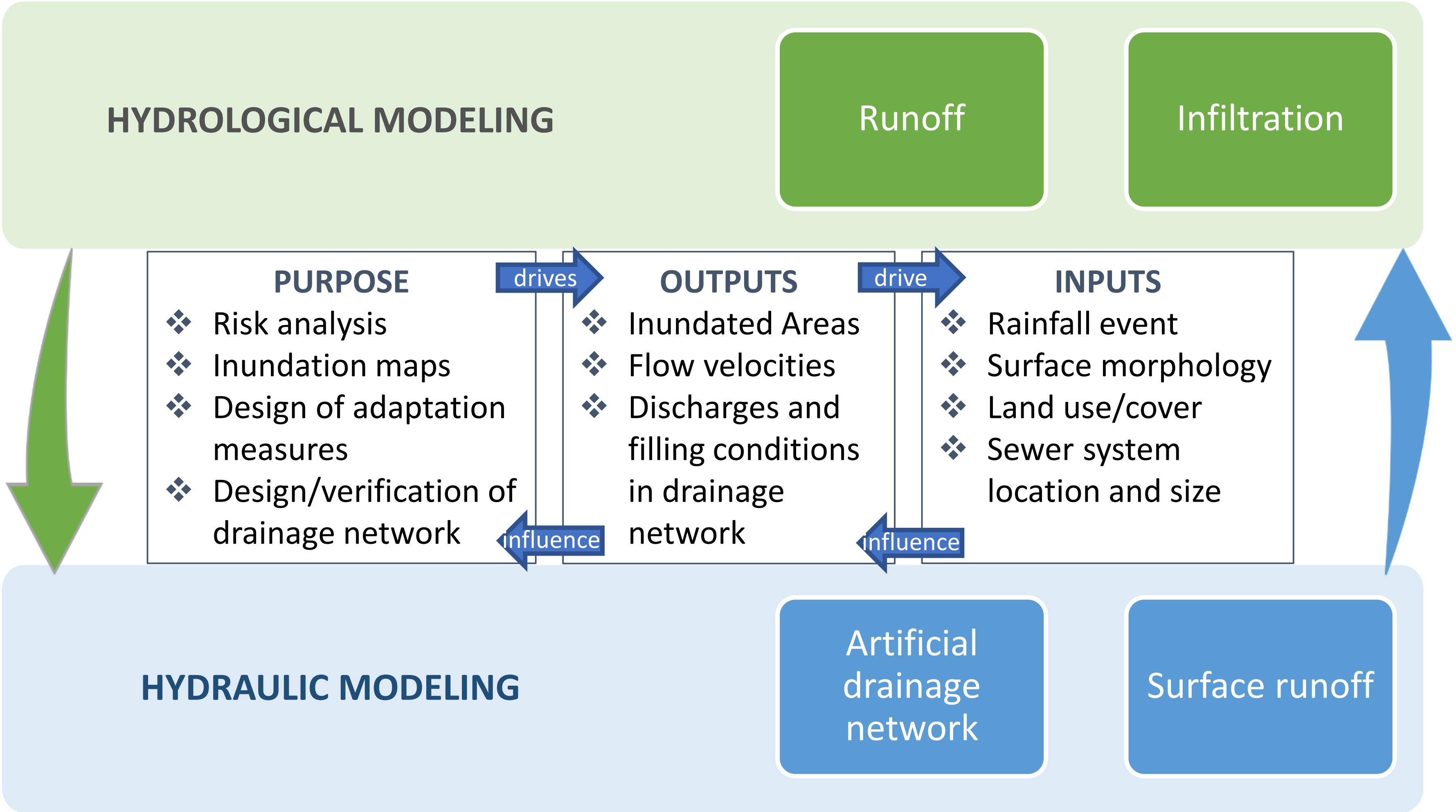
Urban flood modelling

The choice of the specific modelling tool strictly depends on the variety, quality and quantity of available data and on the purpose of the analysis



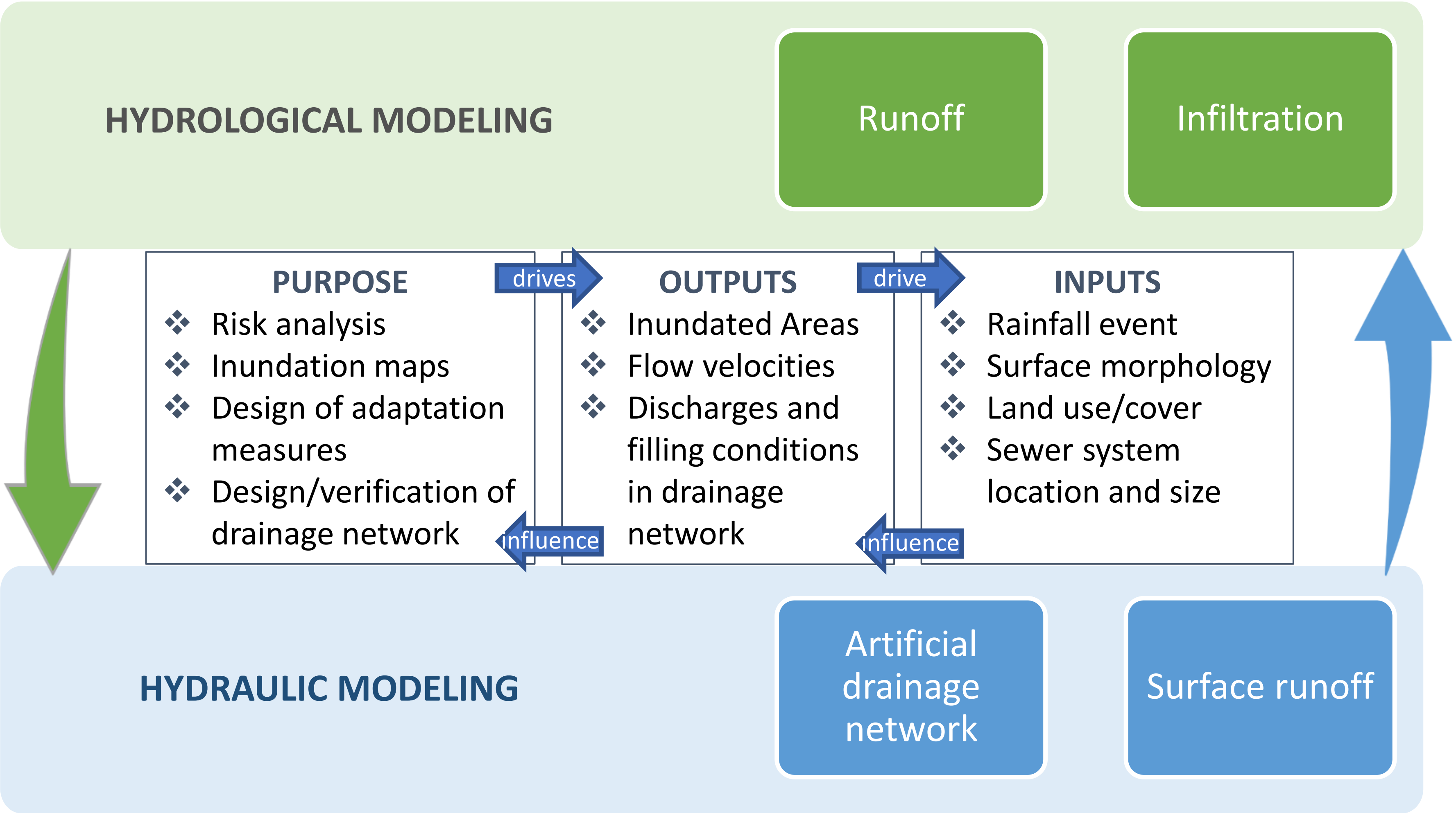
Urban flood modelling

Generally speaking, if high-resolution and complete data is available, coupled 1D-2D models can be applied. Otherwise, one should focus either on the artificial drainage network (e.g. EPA-SWMM) or on surface inundation models (e.g. CADDIES)



Urban flood modelling

Given the high uncertainty levels associated to all the estimations concerning climate change, a particularly useful approach is ***scenario analysis***



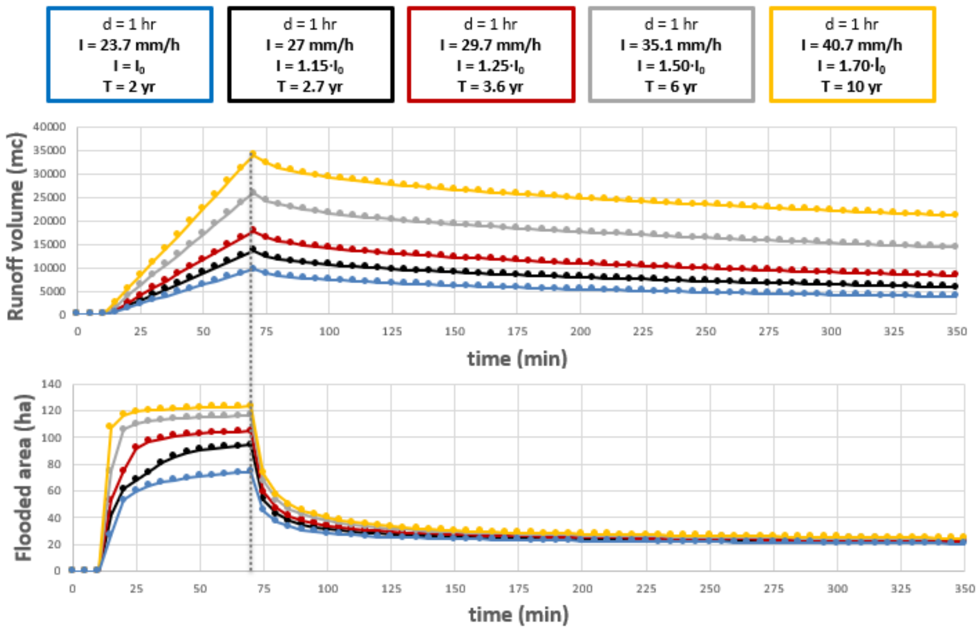
Urban flood modelling

Scenario analysis

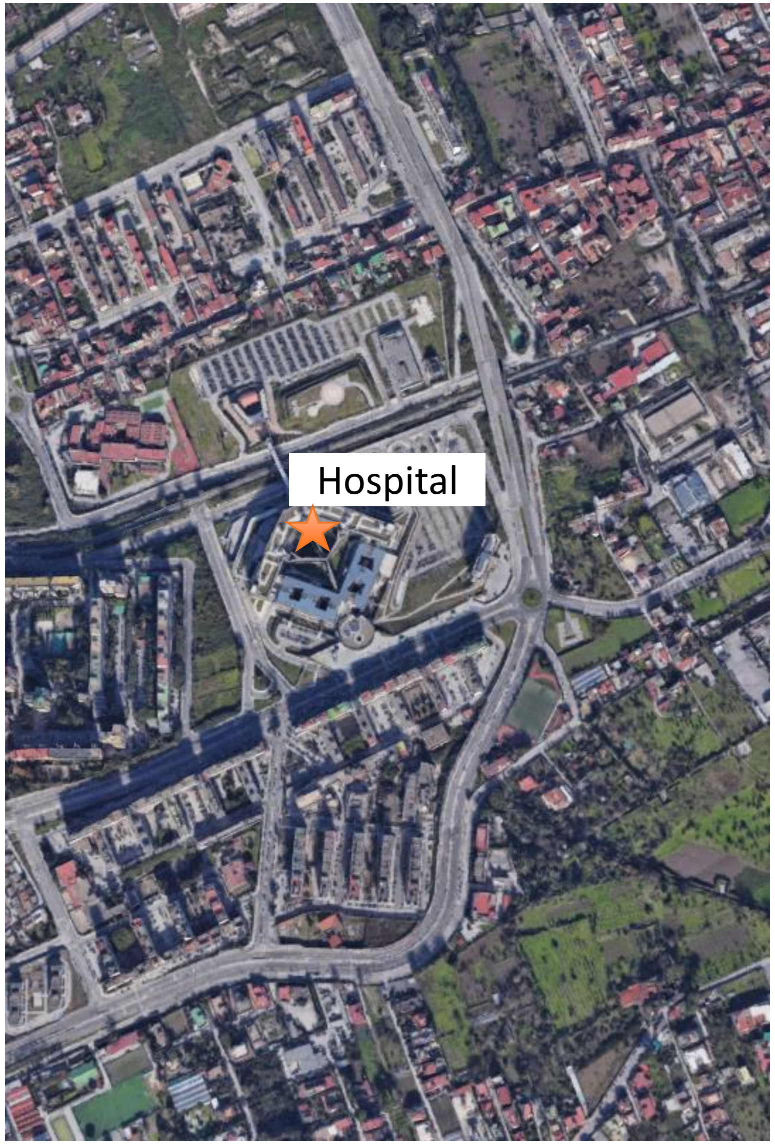
Scenario analysis consists in **performing multiple flood simulations** changing some input parameters, and comparing related results to isolate the effect of one particular parameter.

This approach is still valuable when, as usually occurs, **no flood observations** can be used to validate the flood model.

In a **climate change perspective**, scenario analysis is usually performed by changing the rainfall input.



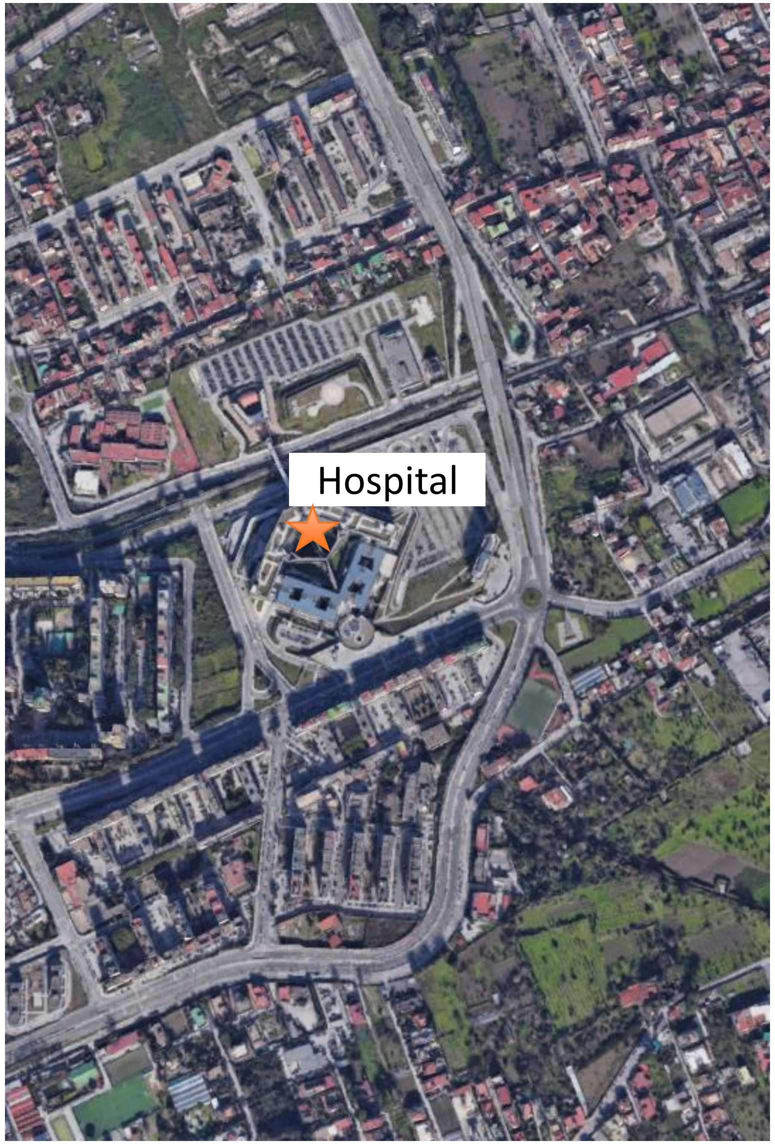
Let’s make an example: Naples, Italy



Let’s make an example: Naples, Italy

The steps of scenario analysis with a bottom-up approach:

1. Identify interesting rainfall scenarios
2. Simulate rainfall scenarios
3. Select metrics to analyse results
4. Assess climate change effect



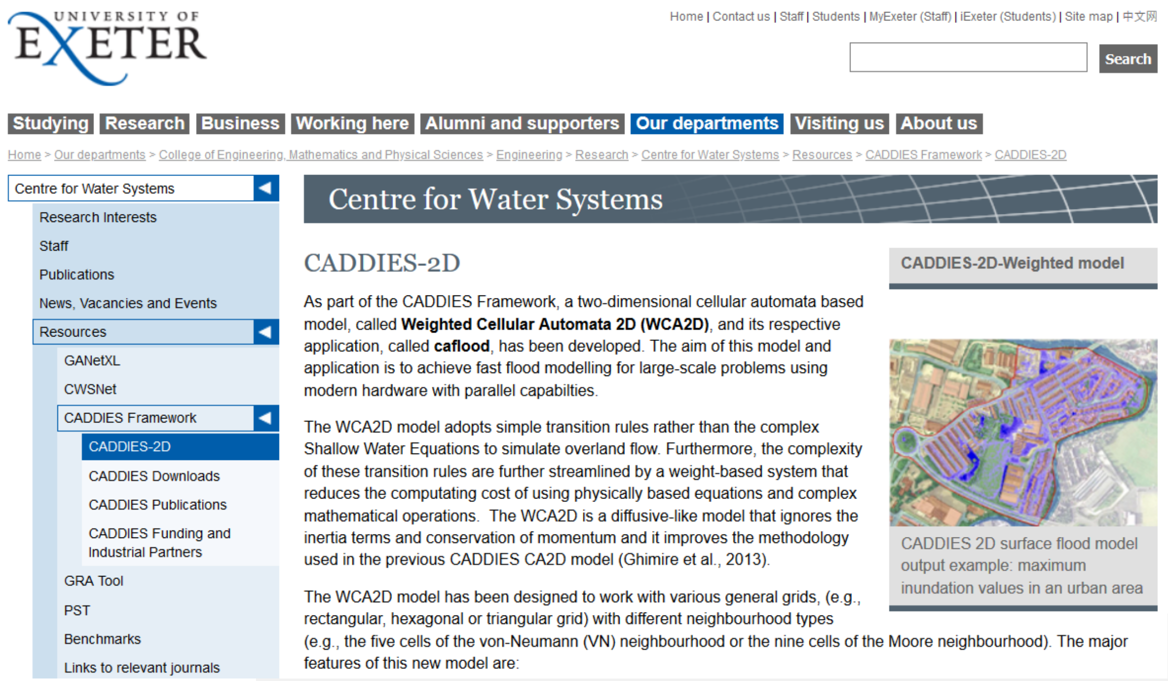
1. Identify interesting rainfall scenarios

For example, constant 1-hr rainfall intensity with return periods of 10, 20, 100, 200 years.
Rainfall values can be estimated by means of local IDF curves or extreme rainfall observations

d = 1 hr I = 40.4 mm/h T = 10 yr	d = 1 hr I = 57.1 mm/h T = 50 yr	d = 1 hr I = 64.3 mm/h T = 100 yr	d = 1 hr I = 71.5 mm/h T = 200 yr

2. Simulate flooding with selected rainfall scenarios

Suppose we are interested in performing surface inundation analysis.
We can decide among the most suitable flood model that provides the results we need, that is surface water depth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CADDIES-2D

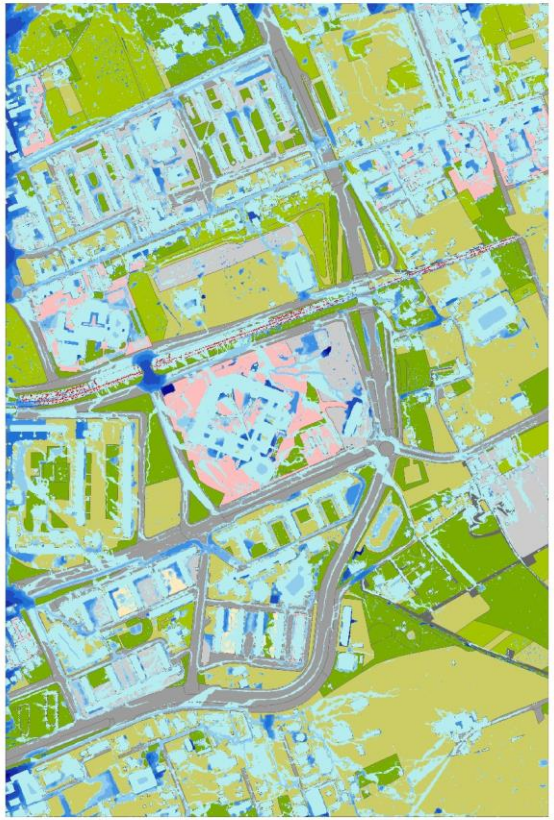
As part of the CADDIES Framework, a two-dimensional cellular automata based model, called **Weighted Cellular Automata 2D (WCA2D)**, and its respective application, called **caflood**, has been developed. The aim of this model and application is to achieve fast flood modelling for large-scale problems using modern hardware with parallel capabilties.

The WCA2D model adopts simple transition rules rather than the complex Shallow Water Equations to simulate overland flow. Furthermore, the complexity of these transition rules are further streamlined by a weight-based system that reduces the computating cost of using physically based equations and complex mathematical operations. The WCA2D is a diffusive-like model that ignores the inertia terms and conservation of momentum and it improves the methodology used in the previous CADDIES CA2D model (Ghimire et al., 2013).

The WCA2D model has been designed to work with various general grids, (e.g., rectangular, hexagonal or triangular grid) with different neighbourhood types (e.g., the five cells of the von-Neumann (VN) neighbourhood or the nine cells of the Moore neighbourhood). The major features of this new model are:

CADDIES-2D-Weighted model

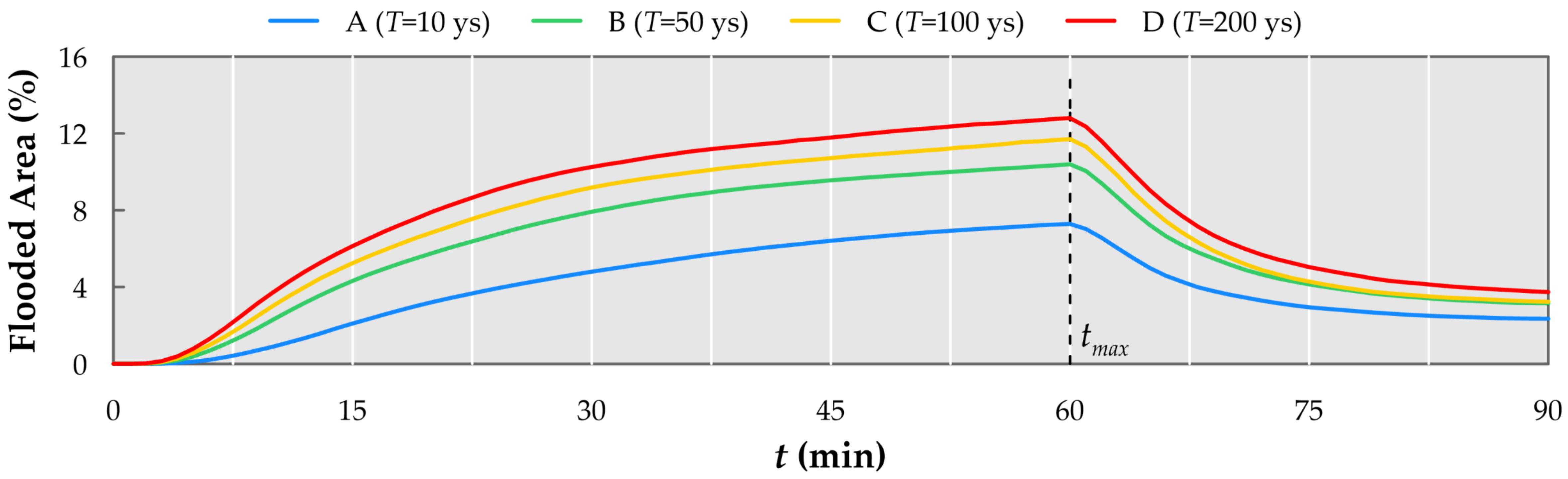
CADDIES 2D surface flood model output example: maximum inundation values in an urban area



Ghimire B., Chen A. S., Guidolin M., Keedwell E. C., Djordjević S., Savić D. A. (2013) “Formulation of a fast 2D urban pluvial flood model using a cellular automata approach”. *Journal of Hydroinformatics* 15, 676.

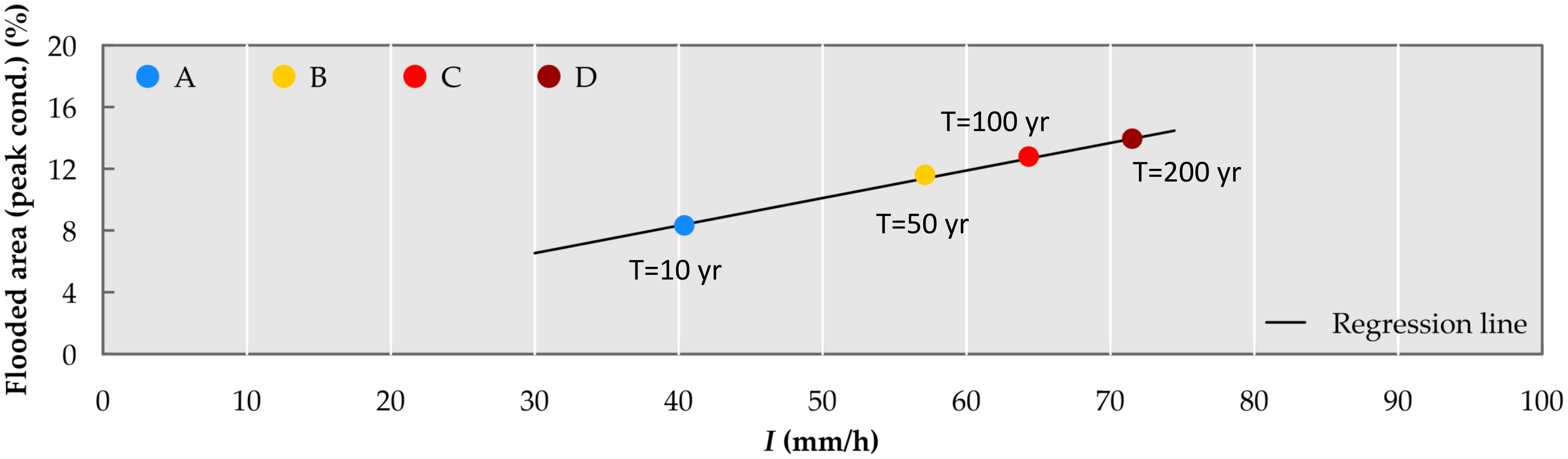
3. Select representative metrics

Flooded Area, expressed as a percentage of the flood-prone area. Cells with water depth lower than 5 cm are considered dry.



3. Select representative metrics

Flooded Area under *peak conditions* (every part of the domain is taken with it maximum water depth experienced during the rainfall event).



4. Assess climate change

Top-down approach

- Compute new rainfall values expected in the future for the same return periods
- Perform additional flood simulations with new rainfall values

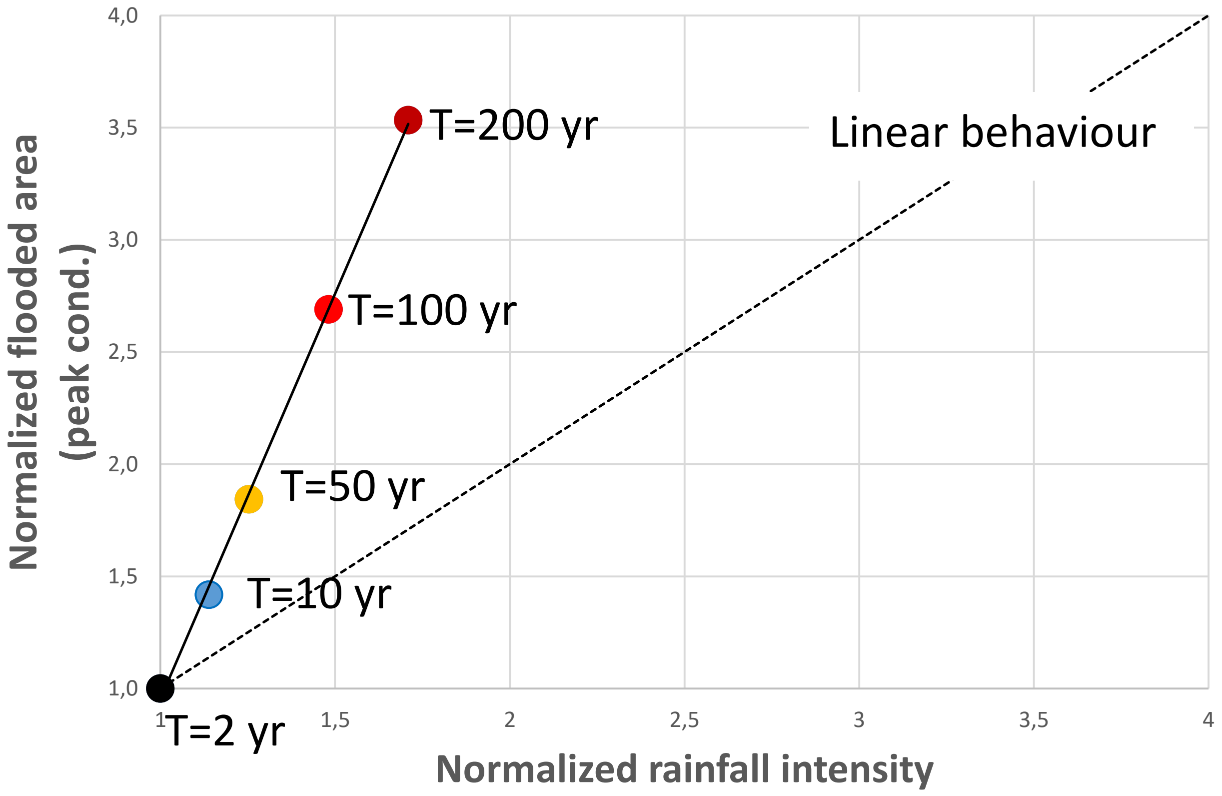
This is more straightforward if downloaded data are used

Bottom-up approach

- Compute new return periods expected in the future for the same rainfall values

This is possible if the equations governing the update of IDF curves are known or can be estimated

5. Urban flood resilience



The rainfall-runoff transformation is such that a small modification in rainfall produces a large modification in flooded areas.

The slope of the curve can be modified for example by introducing drainage solutions.

Thank you!
Any questions?

Centro Euro-Mediterraneo sui Cambiamenti Climatici